Patent Application of

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for

METHOD AND APPARATUS FOR USING FREQUENCY DIVERSITY TO SPATIALLY SEPARATE WIRELESS COMMUNICATION SIGNALS

FIELD OF THE INVENTION

This invention relates to spatial processing of wideband and multicarrier signals in a multipath environment.

BACKGROUND OF THE INVENTION

Beamforming is a technique for providing an array of transducers with directional receiving and transmitting capabilities. An antenna array can implement same-cell frequency reuse by processing signals according to their angle of arrival at the array. The array can send and receive signals in the same frequency band by using separate beams. Beamforming helps to minimize crosstalk and maximize the desired signal for each receiver. Array processing allows for spatial division multiple access, which is described in U.S. Pat. Nos. 5,828,658, 5,642,353, 5,625,880, 5,592,490, and 5,515,378.

An antenna array can be used to mitigate the effects of multipath fading. In a multipath environment, signals received by a mobile receiver have a rapidly changing signal power and a slowly changing mean value. The rapidly varying component can be characterized by Ricean or Rayleigh distributions. Spatial diversity is achieved by separating the antennas in an array, which mitigates fading because deep fades typically do not occur

simultaneously at spatially separated antennas. The use of transmitting and receiving antennas to average the effects of fading is described in U.S. Pat. Nos. 5,437,055, 5,513,176, and 5,577,265, Beam-pattern diversity is achieved by combining line-of-sight and reflected transmissions arriving at the array.

Spatial interferometry multiplexing (SIM) is a technique that uses multipath fading to improve spatial demultiplexing performed by an array. SIM involves a cancellation technique that exploits spatial variations in the complex gain of signals received by the array. SIM is described in U.S. Pat. Appl. 08/862,859 and U.S. Pat. Appl. 09/324,206, which are incorporated by reference.

Frequency diversity mitigates signal loss due to deep fades. Frequency diversity is regarded as a superior means for combating multipath fading. Therefore, wideband protocols (such as the multicarrier protocols described in U.S. Pat. Nos. 5,519,692, 5,504,783, and 5,563,906) have been proposed because they offer benefits such as reduced transmission power and minimum power variations in received signals.

In U.S. Pat. Appl. No. 09/022,950, applicant describes a multicarrier spread-spectrum protocol called Carrier Interference Multiple Access (CIMA). CIMA is based on the understanding that any signal can be broken down into multiple frequency components. Therefore, signal components with specific frequencies, amplitudes, and phases can be combined to create any desired transmit signal. The construction of communication signals based on the CIMA protocol provides many advantages to a multiple access scheme. For example, a CIMA protocol simplifies the implementation of a broadband antenna array, such as the array described in U.S. Pat. No. 5,671,168.

The implementation of a broadband array is substantially more complicated than spatially processing narrowband signals. Broadband beamforming weights need to be frequency dependent, thus requiring frequency separation of antenna signals before application of the weights. Digital beamforming for antenna arrays is described in U.S. Pat. No. 5,671,168. The development of the Fast Fourier Transform (FFT) and digital signal-processing microcircuits make it possible to implement digital beamforming processes. However, the complexity of array processing and the physical size of antenna arrays make arrays impractical for most mobile receivers.

SUMMARY OF THE INVENTION

Spatial processing of wideband and multicarrier signals in a multipath environment is achieved by exploiting frequency diversity of signals received by an antenna. The received signals consist of many individual frequency-diverse signals transmitted by spatially separated transmit sources. Each of the received signals have spatial gain distributions (complex amplitude profiles with respect to space or signal bandwidth) that depend on different frequency-dependent multipath fades. Each spatially separated transmit source generates signals that undergo different fades. The frequency component of each transmitted signal undergoes a frequency-dependent fade. The present invention uses the relative spatial gain distributions of the received signals to separate interfering signals.

The present invention also uses the relative frequency-dependent gain distribution of each transmitted signal. Each transmitted signal can be provided with a unique frequency-dependent gain distribution (which is an amplitude-versus-frequency profile) that ensures the spatial gain distributions of the received signals will be unique, even when multipath fading is negligible. The unique gain distributions also allow separation of signals transmitted from co-located transmission sources. Transmission sources are considered to be co-located if they are closely-spaced or overlapping in spatial proximity. An antenna array is considered a plurality of co-located transmitters when it generates a plurality of beam patterns.

Information signals modulated onto carriers or otherwise spread in frequency can be separated and determined by the SIM processing methods described in U.S. Pat. Appl. 08/862,859 and U.S. Pat. Appl. 09/324,206. Signals received by a single antenna or an array of antennas are separated with respect to frequency (into spectral components) and then spatially separated in a spatial demultiplexer. Spatial demultiplexing techniques in SIM include constellation methods, multi-stage matrix solutions, and multistage weight-and-sum processes.

Benefits of the present invention are realized by using any type of signal diversity in SIM processing. Diversity includes, but is not limited to frequency diversity, polarization diversity, and spatial diversity.

An object of the present invention is to enable a receiver with a single antenna to spatially demultiplex received signals.

Another object of the invention is to use multipath fading to improve the performance of a communication system.

Another object of the invention is to enable a communication system to spatially demultiplex received signals in any type of multipath-fading environment.

The objects of the present invention recited above, as well as additional objects, are apparent in the description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a block diagram of a receiver of the present invention.

FIG. 2A is a graphic representation of an amplitude-versus-frequency profile of a transmitted broadband signal.

FIG. 2B is a graphic representation of an amplitude-versus-frequency profile of a received broadband signal.

FIG. 2C is a graphic representation of an amplitude-versus-frequency profile of a plurality of received broadband signals.

FIG. 3 shows a spatial demultiplexer of the present invention.

FIG. 4 shows a diversity receiver and spatial demultiplexer of the present invention designed to receive and separate multiple interfering broadband signals.

FIG. 5A is a block diagram of a training method of the present invention.

FIG. 5B is a block diagram of a signal-separation method of the present invention.

FIG. 5C is a block diagram of a signal-determination method of the present invention.

FIG. 6A is a table of possible received signal values.

FIG. 6B shows the relative amplitudes of possible received signals from three different frequency samples.

FIG. 7 shows a frequency-diverse receiver and spatial demultiplexer for spatially demultiplexing received signals.

FIG. 8 shows a frequency-diverse receiver and spatial demultiplexer for spatially demultiplexing received signals.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

U.S. Pat. Appl. No. 09/324,206 describes the use of SIM for processing signals that have a multicarrier protocol (e.g., CIMA). SIM exploits multipath fading that occurs between the different frequency (spectral) components. Thus, frequency diversity of the received multicarrier signals enhances the SIM technique. Several spatial-demultiplexing techniques are described in U.S. Pat. Appl. No. 09/324,206, which is hereby incorporated by reference.

The present invention is based on the realization that any received signal can be separated or sampled to provide multiple frequency components and that information spread across the bandwidth of multiple received signals can be recovered if the received signals have unique amplitude-versus-frequency profiles (frequency-dependent gain distributions). Frequency-dependent gain distributions of received signals differ if frequency-diverse (e.g., broadband) transmit signals undergo different fades in a multipath environment. Frequency-dependent gain distributions of received signals can differ by providing different frequency-dependent gain distributions to the transmit signals. The preferred embodiments illustrate examples of separating (1) multiple received signals into frequency components and (2) information streams from the frequency components (or determining the information on each of the received signals) by exploiting the frequency diversity of communication signals in a multipath environment.

FIG. 1 shows a block diagram of a digital frequency-domain implementation of the present invention. A continuous broadband signal $x(t)$ is received at an antenna 158. In an N-user system, the received signal $x(t)$ is comprised of N broadband components $x_n(t)$. If each of the users (or transmit sources) is spatially separated in a multipath environment, N distinct communication channels can occupy the same frequency band.

The continuous Fourier Transforms (spectral components) of the received signal are X(f), where $f_1 \le f \le f_M$. The range of frequency f is denoted by center frequencies $f_1,...,f_M$ for a set of M adjacent frequency bins that span the frequency band of the received signal x(t).

The received signal x(t) is digitized by an analog-to-digital converter 106 that samples the received signal x(t) at equal time intervals at a rate of f_s. The analog-to-digital converter 106 may be preceded by an anti-aliasing filter (not shown). The digital version of the received signal x(t) is:

$$x(k) = \sum_{n=0}^{N-1} x_n(k)$$

The digitized signals x(k) are spectrally decomposed by a filter bank 156. In this case, the digitized signals x(k) are decomposed by an M-point Discrete Fourier Transform (DFT) into M frequency bins. A frequency bin represents the frequency band of each filter in the filter bank. The M-point DFT of x(k) is denoted by X(m), where m=0,...,M-1.

$$X(m) = \sum_{n=0}^{N-1} X_n(m)$$

A spatial demultiplexer 206 weights and combines the spectral components X(m) to separate at least one of the N-user signal components $X_n(m)$. The spatial demultiplexer 206 has a multiplying unit (not shown) where each digitized spectral component X(m) is multiplied by a weight $w_n(m)$. Each of the weights $w_n(m)$ corresponds to one or more weights required to separate a particular signal from the interfering N-1 signals.

In a multipath fading environment, signals $s_n(t)$ transmitted by each of the spatially separated N transmitters have a unique spatial gain distribution upon reception. Therefore, the frequency-dependent gain distribution of each of the received signals is unique at a single spatial location.

FIG. 2A shows an amplitude-versus-frequency profile 71 of a transmitted signal. As the signal propagates through a multipath environment, reflections occur and the amplitude-versus-frequency profile of the signal changes according to constructive and destructive superpositions of the reflected signals. FIG. 2B shows an amplitude-versus-frequency gain distribution 72 of a received signal after it has propagated through a multipath environment. The gain distribution of each received signal corresponds to a

unique set of gains that are frequency dependent and that depend on the spatial locations of the transmitters (N users). FIG. 2C shows an amplitude-versus-frequency gain distribution 73 of a superposition of a plurality of received signals.

The frequency-dependent gain distribution causes each of the frequency components $X_n(m)$ to have a complex-valued channel factor β_{mn} relative to the mth frequency and the nth communication channel.

$$X(m) = \sum_{n=0}^{N-1} \beta_{mn} X_n(m)$$

The spatial demultiplexer 206 applies weights $w_n(m)$ to the frequency components $X(m)$. The weights $w_n(m)$ are determined from the channel factors β_{mn} such that interfering signals are separated from one or more desired signals. The spatial demultiplexer 206 combines the weighted signals $w_n(m)X(m)$ in a combiner (not shown), which may be a multistage combiner (shown in FIG. 3) to remove a plurality of the interfering signals from the desired signals.

The spatial demultiplexer 206 shown in FIG. 3 is a multistage type of demultiplexer that weights and combines input signals in order to separate interfering signals. Each of a plurality (in this case, three) of inputs 201, 202, and 203 is provided with a measurement from a different frequency sample. Up to three interfering signals can be separated using the spatial demultiplexer 206 shown. The function of the spatial demultiplexer 206 is described in U.S. Pat. Appl. 09/324,206.

An illustration of the basic components used for performing SIM is shown in FIG. 4. A plurality of spatially separated transmit sources 99 transmit signals that occupy the same frequency band and, thus, interfere with each other at a diversity receiver 157. The diversity receiver 157 includes an antenna or other type of sensor (not shown), preprocessing systems (not shown), and a filter bank (not shown). The diversity receiver 157 provides a plurality of output signals to the spatial demultiplexer 206. The output signals represent different samples of the receive signals. The samples may be frequency samples, polarization samples, spatial samples, or any other type of sampling of a multiplexing means affected by a multipath environment.

The transmit sources 99 may be different system users or they may be an array (or group) of transmitting elements that are operated by one or more users. The transmit

sources 99 may be co-located if each of the transmit sources 99 has a different beam pattern (to provide different multipath characteristics at the receiver), or if each of the transmitted signals has a unique amplitude-versus-frequency profile or polarization.

The amplitude-versus-frequency profiles of the transmitted signals (such as the amplitude-versus-frequency profile 71) may be made different for different transmit signals. Adjustments to a profile may be made at the transmitter by a frequency-dependent amplitude-adjustment means such as a frequency-domain filter (not shown). Although code modulation of carriers is performed by multicarrier protocols (such as multicarrier CDMA), the received multicarrier signals are separated by decoding, and the degree of separation is determined by the orthogonality of the codes. However, adjustment to the amplitude-versus-frequency profile of the transmitted signals in a SIM system has the same effect as changing the multipath environment of the signals. Different adjustments to the transmit-signal profile (such as the profile 71 shown in FIG. 2A) provides different receive-signal profiles (such as the profile 72 shown in FIG. 2B) and, thus, simulates different multipath environments. Therefore, the desired effect of changing the amplitude-versus-frequency profile of transmitted signals is to change the effective multipath environments of the transmitted signals to facilitate separation (or detection) of the signals using one of the SIM processes (which includes constellation methods).

One objective of providing each transmit source 99 with a unique amplitude-versus-frequency profile is to ensure that SIM methods can be performed despite the multipath characteristics of the propagation environment. Thus, received signals are separable by SIM even in environments where multipath fading is negligible.

The diversity receiver 157 may combine different types of diversity. For example, the diversity receiver 157 may have multiple antennas (spatial diversity) or multiple polarization detectors (polarization diversity) in addition to a filter bank (not shown).

Due to effects such as shadowing and different transmitter beam patterns, the channel factors β_{mn} of signals received from two or more transmitters in close proximity to each other may be substantially different. In conventional beamforming techniques, it is difficult to discriminate between transmit sources that are in close proximity or that are

collinear. Therefore, the SIM method provides superior spatial demultiplexing and frequency reuse than conventional array-processing methods.

In the present invention, mobile units (as well as stationary units like base stations) may spatially demultiplex receive signals using the SIM technique. In this case, the signal inputs to a spatial demultiplexer are the complex-valued information signals obtained from each of the different frequency components. Therefore, a frequency filter and single antenna at a receiver provide the necessary inputs to the spatial demultiplexer. Multiple antennas may also be used wherein the spatial demultiplexing enabled by frequency diversity assists or complements array processing.

Some array processing techniques described by Liu in U.S. Pat. No. 5,671,168 are applicable to the methods of processing signals described herein. The symmetry of the Fast Fourier Transform may be used to reduce the complexity of signal processing operations. Redundant terms in the DFT may be removed by a spectral filtering means (not shown). Liu also describes how the redundant terms can be reconstructed using a complex conjugation operation. The operation of the filter bank 156 may be performed using an output pruned Fourier Transform. Time interpolation through DFT may be used to obtain high-precision time shifting without increasing the sampling rate f_s. Liu describes combinations of these techniques and others for reducing quantization and digitization errors; these are also applicable to the present invention.

Determination of the weights $w_n(m)$ may be performed by a training sequence or estimated during normal communications. A training sequence is performed when transmitters transmit known data, and the received data is compared to the known data to determine the channel characteristics. Training sequences may be transmitted in channels that are separate from other communications. Channels may be separated by time, frequency, phase, polarization, spread-spectrum coding, or other modulation techniques. Techniques known as open-loop methods may be performed by the present invention to estimate the channel characteristics used to determine the weights $w_n(m)$.

Closed-loop techniques use feedback from receivers to estimate channel characteristics. A probing-feedback method that allows an estimation of the instantaneous channel vector is described in U.S. Pat. No. 5,471,647, which is hereby incorporated by reference. The probing-feedback method is further described in the following articles,

which are also incorporated by reference: "Spectrum Reuse Using Transmitting Antenna Arrays with Feedback," *Proc. International Conference on Acoustics, Speech, and Signal Processing*, pp. 97-100, April 1994; and "Adaptive Transmitting Antenna Arrays with Feedback," *IEEE Transactions on Vehicular Technology*. Feedback from receivers in the present invention may be used to identify channel parameters and form the weights $w_n(m)$ by any of the optimal combining methods, such as maximum ratio and equal gain combining. A method for minimizing crosstalk and reducing feedback in a closed-loop system is described by U.S. Pat. No. 5,634,199 which is hereby incorporated by reference. The open-loop and closed-loop methods may be used in the present invention to provide power control, adjustment to transmit signal gain distributions, and beam-pattern adjustment to transmitting units.

A training method for SIM is shown in FIG. 5A. A first step of receiving communication signals 20 is followed by an optional preprocessing step 22. Preprocessed signals are filtered in a filter step 24. The filtered signals are used to build weights or a constellation of points in an evaluation step 29.

Reception of communication signals may be performed by a single sensing element or an array of sensors. The received signals may be referenced to known or estimated transmit signals. Although the examples described in the invention are directed toward radio communication systems, the system and method of the present invention may also be used for remote sensing, navigation, and surveillance applications. The present invention may also be used to process any type of electromagnetic signals (such as infrared, light, and x-rays) and vibrational signals (such as acoustic signals and sonar). The received signals may be provided to the sensors by a free-space interface or a waveguide interface.

The reception step 20 may optionally be followed by the preprocessing step 22 in either the training process or the measurement process. The preprocessing step 22 involves signal-processing applications such as (but not limited to) sampling, anti aliasing, spread-spectrum coding and or decoding, and prefiltering. For example, a multicarrier CDMA signal may be decoded in the preprocessing step by multiplying each of the received carriers with an inverse chip sequence of a particular spreading code. Multiple signals

that use the same spreading code will be separated by spatial demultiplexing steps in the demultiplexing operations shown in FIG. 5B and FIG. 5C.

The filter step 24 provides frequency separation of the components of the received signal. The filter step 24 may include any means of separating or detecting frequency components so a plurality of frequency components (or representations of frequency components) are provided to a next processing step.

The evaluation step 29 involves evaluating filtered signals output from the filter step 24 during a training phase. The evaluation step 29 may include estimations of the radio channels and the development of weights based on the channel estimations. The weights may be based on the amplitude and/or phase of the filtered signals. The evaluation step 29 may also establish one or more constellations of points that may be used to estimate unknown transmit signals received by the system or evaluate the accuracy of signal estimates. The evaluation step 29 may include a signal-to-noise or signal-to-noise-plus-interference evaluation to optimize the accuracy of weights and/or constellations. The evaluation step 29 may also control the training processes and/or the transmit characteristics of transmitters that produce signals received by the system.

FIG. 5B shows a measurement process for a SIM method that employs a weight-and-sum or an equivalent method of solving multiple equations and unknowns. A spatial demultiplex step 26 follows the filter step 24. In the spatial demultiplex step 26, each of the received frequency components is evaluated by either or both its amplitude and phase. The number of frequency components may provide an upper bound to the number of equations the spatial demultiplexer may use to separate received signals. However, the spatial demultiplexer may create a number of equations that exceeds the number of frequency components by making use of spatial diversity (more than one receive antenna), time diversity, polarization diversity, or any multiple-access techniques (such as spread-spectrum code separation). If the number of distinct equations (demultiplexer inputs) is equal to or greater than the number of unknown transmit signals, the transmit signal can be determined explicitly.

A decision and control step 28 may provide estimations of the signals output from the spatial demultiplex step 26. The decision step 28 may also evaluate the accuracy of the estimates and initiate actions, such as requesting a training session, adjusting weights

or constellation points, and controlling transmit characteristics (e.g., antenna beam patterns, amplitude-versus-frequency profiles, signal timing, frequency, spread-spectrum code, and polarization) of remote transmitters.

FIG. 5C shows a measurement process that uses a constellation method for demultiplexing received signals. After the filter step 24, the amplitudes and/or phases of the frequency components of the receive signals are measured in a measurement step 25.

During a training sequence, a constellation of points may be generated for each of the frequency components by measuring or estimating the amplitude and/or phase of possible combinations of transmit signals that can be received. For example, each transmitter may transmit a predetermined sequence of known data bits simultaneously with predetermined transmissions from other transmitters. The sum of the signals received by one or more receivers at different time intervals in the training sequence may cycle through all of the receivable signal combinations. Either or both the amplitude and phase of the signals received in each of the training time intervals forms a constellation point. The signal characteristics of each frequency component recorded for each of the training time intervals form a constellation of points that map to the data transmissions. Similarly, each transmitter may separately transmit a predetermined training sequence of data that is used to calculate the amplitude and/or phase characteristics of the possible signal combinations.

The possible combinations of three signals having data bits of 1 or 0 are shown in FIG. 6A. Each possible combination of data, which is shown in a data combinations table 31, is identified by a combination identifier α_j (shown in a table 33), where $j = 1,...,J$ and J is the number of possible combinations.

FIG. 6B shows three amplitude profiles (constellations) of data combinations α_j. The amplitude profiles correspond to three different frequency components f_1, f_2, and f_3. Signal phases may be combined with the amplitude profiles to form three-dimensional constellations or the phases may provide additional two-dimensional constellations. Increasing the number or dimension of constellations can allow a more accurate estimation of received signals. For example, a measured data point for frequency component f_1 may be in close proximity to constellation points α_5, α_2, and α_8. The placement of the measured data point for frequency component f_2 may be between the

closely-spaced points α_5 and α_8 in the f_2 constellation. Thus, the second measurement removes the uncertainty that the data may correspond to α_2. A measurement of the f_3 component clearly defines which constellation point α_5 or α_8 corresponds to the measurement because the points α_5 and α_8 in the f_3 constellation are far apart. Using the constellation method can remove the requirement that the number of frequency components at least equal the number of transmitters. However, it is preferable to use large numbers of constellations or constellations with large numbers of dimensions in order to provide accurate estimations of received signals.

In a normal communication mode, unknown data signals are received, preprocessed (optional), filtered, and then measured. The measured frequency components may be weighted before comparison to a constellation that has also been weighted. Constellations may be weighted with complex weights during training or estimation to separate closely spaced constellation points. The measured signal amplitude and/or phase of each frequency component is compared to a constellation of points in a comparison step 27. Comparisons may be made relating the proximity of each measured value to one or more points in its associated constellation. For example, the difference between measured values and constellation points may be forwarded to the decision and control step 28. The decision step 28 may update points in the constellations to adapt to changing multipath characteristics indicated by the measurements.

A SIM processor shown in FIG. 7 separates a plurality of received signals having unique spatial gain distributions with respect to frequency. A frequency-diversity receiver 157 includes a single antenna 158 and three frequency filters 159A, 159B, and 159C that separate carrier signals by frequency. The transmit signals $s_n(t)$ may be separated from the carriers by the receiver 157 before processing by a constellation type of spatial demultiplexer 309. Optionally, the spatial demultiplexer 309 may weight the frequency components before combining the signals. In the SIM processor shown in FIG. 7, at least two constellations are created and at least two parallel signal measurements are performed before they are compared to the constellations. Outputs 251 and 252 of the spatial demultiplexer 206 are evaluated in a decision processor 120. Estimates of at least two interfering signals are provided at output terminals, such as output terminals 254 and 255.

A SIM processor that provides a multistage weight-and-sum or equivalent matrix solution is illustrated in FIG. 8. A frequency-diversity receiver 157 separates received signals into a plurality of frequency bands and couples the frequency components to a spatial demultiplexer 206. The spatial demultiplexer 206 performs a weight-and-sum or equivalent operation to separate a number n of unknown signals from a number m of measurements, where the number m of measurements is preferably greater than or equal to the number n of unknown signals.

The methods of using frequency diversity (described herein) for separating interfering signals transmitted by spatially separated transmitters in a multipath-fading environment may be applied to separating received signals having different polarizations. The multipath environment can provide different degrees of depolarization relative to spatial locations of the transmitters. However, even co-located transmit sources can provide polarization diversity at a receiver by transmitting different polarizations. Similarly, spatial demultiplexing of polarized signals may be performed in an environment with insignificant multipath if each transmitter provides a signal having a different polarization. Polarization types that may be used in the present invention include linear and circular polarization.

Another application of the present invention is the separation of interfering signals that have quadrature and in-phase components. Different ratios of amplitudes between quadrature and in-phase components may be processed to help identify (and separate) signals between different transmitters. Similarly, signals having unique amplitude ratios between different polarizations enables separation of interfering signals at a receiver.

In the preferred embodiments, several kinds of spatial interferometry are demonstrated to provide a basic understanding of diversity reception and spatial demultiplexing. With respect to this understanding, many aspects of this invention may vary. For example, the antenna array may be an array of individual antennas or a multiple-feed single-dish antenna where each feed is considered to be an individual antenna element. Although only two- and three-element spatial demultiplexers are shown, spatial demultiplexing processes may be performed on a larger number of inputs. The complexity of the spatial demultiplexer process typically increases for larger numbers of